3 Predictive Models

Diverging Wave Direction

The dominant vessel-generated waves, as they travel out from the sailing line, are the diverging waves. They travel in the direction θ with respect to the vessel sailing line. As discussed θ varies from 35°16' for deep water to zero degrees for a Froude number of unity. Using these theoretical limits and the available experimental data, Weggel and Sorensen (1986) developed the empirical equation

$$\theta = 35.27\,(1 - e^{12(F-1)}) \qquad F < 1 \tag{4}$$

where θ is given in degrees and F has values between 0 and 1.0.

For Froude numbers in excess of unity, the direction of propagation of the vessel-generated waves can be determined from Equation 3 with $\theta = 90° - \alpha$.

Wave Period and Length

The celerity of the transverse waves is equal to the vessel speed. The celerity of the diverging waves can be determined from Equation 1 with θ determined from Equation 4 for a given vessel speed and water depth. Given the wave celerity, the length L and the period T of the transverse or diverging waves can be calculated from Equations 5 and 6, respectively.

$$C^2 = \frac{gL}{2\pi} \tanh \frac{2\pi d}{L} \tag{5}$$

$$T = \frac{L}{C} \tag{6}$$

Equation 5 can be solved by trial and error; then Equation 6 can be solved directly for the wave period.

Wave Height

The vessel-generated wave height is more difficult to predict. This is because it is dependent on more than the vessel speed and the water depth. Vessel-generated wave height is dependent on the bow geometry, the operating draft of the vessel, the distance from the sailing line, and in relatively confined channels, the clearance between the vessel hull and the channel bottom and sides. Also, the wave height varies throughout the wave pattern so one must define which wave height is being predicted. Most commonly the wave height reported for field and laboratory measurement programs and used for all height prediction models is the maximum wave height H_m from the wave record as depicted in Figure 4.

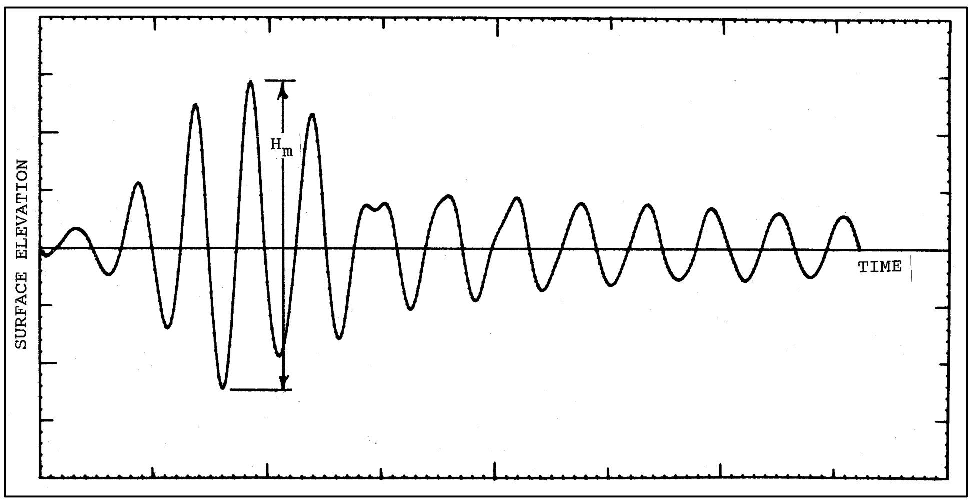

Figure 4. Typical vessel-generated wave record with H_m denoted

In a small number of studies the authors have defined an average or root mean square wave height from the wave record. This approach has a serious limitation in that the magnitude of the resulting wave height depends on the length of record being considered (Figure 4).

If the Froude number is greater than about 0.7 and/or the vessel draft to water depth ratio is large (approaching unity), the water depth will affect the resulting height of the wave being generated by a vessel. Wave height models should account for these effects. A separate, but possibly important, consideration is the possible additional change in wave height owing to depth effects as a wave propagates over an uneven bottom. That is, when the water depth to wave length ratio is less than a half, the wave height can be affected by refraction and shoaling effects. Refraction will also change the orientation of the wave crest. These effects can be reasonably estimated if the bottom hydrography is known, using standard wave analysis techniques.

One approach to predicting the wave height generated by a given vessel and operating condition is to search the literature of field and laboratory investigations for results from a similar vessel and operating condition. The following references contain measured vessel wave information that may be of use in making wave height predictions:

a. Bhowmik (1975).

b. Bhowmik, Demissie, and Guo (1982).

c. Bhowmik et al. (1991).

d. Bidde (1968).

e. Brebner, Helwig, and Carruthers (1966).

f. Das (1969).

g. Hay (1967).

h. Johnson (1958).

i. Kurata and Oda (1984).

j. Maynord and Oswalt (1986).

k. Nece, McCaslin, Christensen (1985).

l. Ofuya (1970).

m. Sorensen (1966a).

n. Sorensen (1966b).

o. Zabawa and Ostrom (1980).

An empirical equation or data plots may be provided in the above references, but measured data may not be tabulated, or only selected data are shown to demonstrate a point made in the paper.

Some authors have developed equations for the prediction of H_m as a function of dependent parameters such as vessel speed, distance from the sailing line, water depth, and simplified hull geometry parameters. These equations are typically regression analyses of data collected by the author with, in some instances, adjustment to satisfy some theoretical considerations. Most of the equations only employ the data set collected by the author and thus are limited to the vessel type and operational conditions that the author's data represent. These wave height prediction models are presented below

Model 1 (Balanin and Bykov)

Balanin and Bykov (1965) presented two equations based on Russian design practice that may be combined to yield an equation for the vessel wave height (presumably H_m) at the channel bank.

$$H_m = \frac{1.25\,V^2}{g}\left[1-\left(1-\left(4.2+S_c\right)^{-1/2}\right)\left(\frac{S_c-1}{S_c}\right)^2\right]\left[\frac{2+\sqrt{w/L_v}}{1+\sqrt{w/L_v}}\right] \tag{7}$$

S_c is the channel section coefficient which is the channel cross-section area divided by the wetted cross-section area of the vessel at midship, w is the channel width at the water surface, and L_v is the vessel length.

It appears that this equation is applicable only to navigation canals of fairly restricted width. The decrease in wave height with distance from the bow does not appear to follow anything like the theoretical inverse cube root relationship discussed above. It probably only applies to a fairly restricted class of vessels that were in use on the canals when the equation was developed.

Model 2 (U.S. Army Corps of Engineers)

An equation that is somewhat similar to but much simpler than Equation 7 was employed by the U.S. Army Corps of Engineers, Huntington District (1980) to predict bow diverging wave heights at the bank in navigation canals. This equation is

$$H_m = 0.0448\,V^2\left(\frac{D}{L_v}\right)^{1/2}\left(\frac{S_c}{S_c-1}\right)^{2.5} \tag{8}$$

where D is the vessel draft. Though this equation was applied on the Ohio River for commercial tows, the actual channel size and vessel used to develop the equation is unknown. It was most likely developed for a restricted channel since distance from the vessel is not employed.

Model 3 (Bhowmik)

Bhowmik (1975) presented the results of a small number of measurements of waves generated by a single vessel moving at three different speeds (7.6, 9.0, and 21.1 mph[1]) and three different distances from a wave gauge. The vessel was 18 ft long, and had a beam of 7.25 ft and a midship draft of 3.25 ft. It displaced about

[1] A table of factors for converting Non-SI units of measure to SI units is found on page vi.

2,200 lb, but no other details were given about the vessel. A regression analysis of the resulting data yielded the following relationship

$$\left(\frac{H_m}{D}\right)^2 = 0.0345\, V^{1.174} \left(\frac{x}{L_v}\right)^{-0.915} \tag{9}$$

where x is the distance from the vessel sailing line to the point of wave measurement and the vessel speed V is in miles per hour.

According to Equation 9, H_m is proportional to $V^{0.587}$ which is much lower than reported by most investigators who show increases to a power greater than unity (typically 2 or higher; e.g., see Equations 7, 8, 10, 15, and 16). One suspects that the vessel was operating normally at the two low speeds and planing at the high speed so that there was no significant change in wave height for the three speeds. H_m is proportional to $x^{-0.46}$ which approximates the theoretical value of -0.333. The water depth is not included in Equation 9 which implies that the equation would only be for deep water waves (i.e., F less than about 0.7). As mentioned above, the tests were only for one vessel with a hull type that is not specified.

Model 4 (Gates and Herbich)

Gates and Herbich (1977) presented a method for predicting the cusp wave height H_m generated by large vessels moving in deep water (i.e., F < 0.7). They start with an equation from Saunders (1957) which gives the wave height being generated at a vessel's bow H_b

$$H_b = \left(\frac{K_w B}{L_e}\right) \frac{V^2}{2g} \tag{10}$$

In Equation 10, B is the maximum beam width of the vessel hull and L_e is the entrance length of the hull defined as the distance along the sailing line from the bow stem back to the point where the parallel middle body begins. (This approach is aimed at large vessels such as cargo vessels and tankers which have a bow located fore of a long middle section having parallel sides. Basically, B/L_e is an indication of the bow angle at the water line.) K_w is a coefficient that Saunders (1957) plotted as a function of the ratio $V/(L_v)^{0.5}$ using data from larger vessels including tankers, liners, a seaplane tender, a gun boat, and a cruiser. This relationship is given in Figure 5 (Saunder's original figure modified by Gates and Herbich to fit experimental data). Since the horizontal scale in Figure 5 is not dimensionless, one must use English units to determine $V/(L_v)^{0.5}$. Using data from sixteen tanker and bulk cargo ships, Gates and Herbich (1977) presented an equation which may be used to estimate L_e for a given vessel length (Equation 11). The equation is

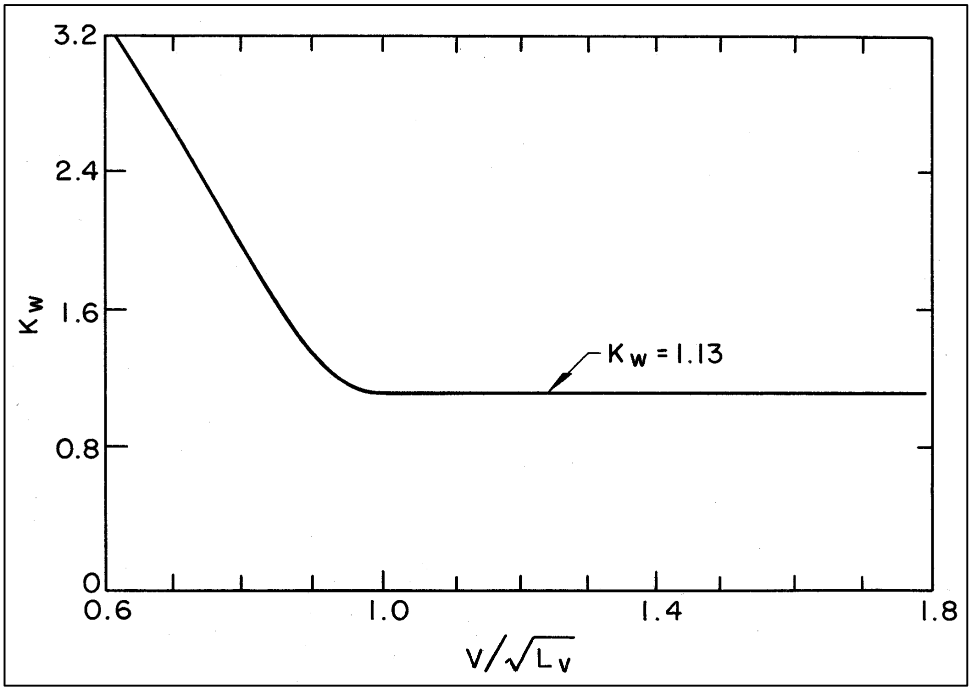

Figure 5. Proposed K_w values for the Gates and Herbich (1977) model

$$\frac{L_e}{L_v} = 0.417 - 0.00235\, L_v \tag{11}$$

To determine the wave height change as a function of distance from the bow, Gates and Herbich (1977) used the theoretical formulations of Havelock (1908) for wave height at the cusp points in deep water. Employing these equations, the distance to any cusp point is given by

$$x = \frac{1.21\, V^2\, (2N + 1.5)}{g} \tag{12}$$

where N = 1, 2, 3 . . . . for the successive cusp points out from the sailing line. Then H_m at these cusp points is given by

$$H_m = \frac{1.11\, H_b}{(2N + 1.5\,)^{0.33}} \tag{13}$$

Gates and Herbich (1977) checked their method against the waves measured by Brebner, Helwig, and Carruthers (1966) for two large vessels at one speed and three and five cusp point distances respectively from the sailing line. The results were quite satisfactory.

Model 5 (Bhowmik, Demissie, and Guo)

Bhowmik, Demissie, and Guo (1982) reported measured vessel wave data from 59 barge tows consisting of from 2 to 18 barges and a tugboat operating on the Illinois and Mississippi Rivers. Vessel group speeds varied from 3.2 to 20.3 ft/sec and wave gauge distances from the sailing line varied from 30 to 700 ft. Channel blockage ratios (reciprocal of S_c) varied from 14.7 to 226.9. Often individual groups of waves could be discerned from the barge tow bow and stern and from the tugboat driving the tow. The authors compared the measured maximum wave heights to those given in Equations 7 and 8, but with little success. They then tried a multivariate regression analysis between the measured wave heights and those parameters they felt were important to wave generation. The best result (correlation coefficient = 0.87) was

$$\frac{H_m}{D} = 0.133 \frac{V}{\sqrt{gD}} \tag{14}$$

Even though the range of vessel speeds was large and it is unlikely that any of the vessels were planing, there is a linear relationship between H_m and V. It does not include the wide range of distances between the sailing line and the point at which waves were measured.

Model 6 (Blaauw et al.)

Blaauw et al. (1984) present an equation that is based on Delft Hydraulics Laboratory field (canal) and laboratory measurements and employs a format similar to Gates and Herbich (1977). The height of the "interference peaks" (i.e., H_m) is given by

$$H_m = Ad\left(\frac{S}{d}\right)^{-0.33} F^{2.67} \tag{15}$$

where S is the distance (perpendicular to the sailing line) from the vessel's side to the point at which the wave height is being calculated (i.e., $S = x - B/2$) and A is a coefficient that depends on the vessel hull type and condition. Given values are: loaded pushing unit $A = 0.8$; empty pushing unit $A = 0.35$, and conventional inland motor vessel $A = 0.25$.

Model 7 (Permanent International Association of Navigation Congresses)

A Permanent International Association of Navigation Congresses (PIANC) working group report on the design of canal revetments (1987) contains an equation similar to Equation 15 for waves generated by vessels in inland waterways. This equation states that

$$H_m = A'' d \left(\frac{S}{d} \right)^{-0.33} F^4 \tag{16}$$

where the coefficient *A*" has a value of unity.

A similar equation is presented in a paper by Verhey and Bogaerts (1989) where the fourth power for the Froude number and and the coefficient *A*" are given based on laboratory and field tests in deep water (i.e., $F < 0.7$). The coefficient *A*" has values of 1.0 for tugs, patrol boats, and loaded conventional inland motor boats (thus Equation 16), 0.5 for empty European barges, and 0.35 for empty conventional motor vessels.

Verhey and Bogaerts (1989) report that an attempt was made to incorporate the bow geometry of the ship in the coefficient *A*" reported above. They give

$$A'' = \frac{KD}{L_e} \tag{17}$$

which uses D/L_e rather than B/L_e (as in Gates and Herbich 1977) to define the bow geometry. They do not give specific values for *K* but say it was determined for a range of vessel types (passenger ships, freighters, tankers, supply boats, ferries, and container ships) and ranged between 1.5 and 4.0. (Note from Equations 16 and 17 that this range of *K* values gives a commensurate range of H_m values.) In their investigations, values of L_e in many cases had to be estimated which led to variation in the results for *K*.

Model 8 (Sorensen and Weggel)

Sorensen and Weggel (1984) and Weggel and Sorensen (1986) developed a vessel wave height prediction model based on the measured laboratory and field data then available in the literature. They noted some of the important limitations on the available data as far as developing a completely satisfactory wave prediction model. They found that:

a. Usually the hull geometry was not well defined. At best the author gave the vessel length, beam, and draft (not always at the water line) and possibly the displacement.

b. Most vessels were operated only at low vessel draft to water depth ratios.

c. The only wave height information reported was H_m.

d. The range of vessel hull types for which wave data were reported was somewhat limited.

e. Vessels were operated over a limited range of Froude numbers.

Their initial model related H_m to the vessel speed, the distance from the sailing line, the water depth, and the vessel displacement volume W. This yielded four dimensionless variables:

$$
\begin{aligned}
F &= \frac{V}{\sqrt{gd}} \qquad & x^* &= \frac{x}{W^{0.33}} \\
H_m^* &= \frac{H_m}{W^{0.33}} \qquad & d^* &= \frac{d}{W^{0.33}}
\end{aligned}
\tag{18}
$$

The basic initial model, in terms of these dimensionless variables, is given by

$$H_m^* = \alpha \, (x^*)^n \tag{19}$$

where α and n are a function of the Froude number and dimensionless depth as follows:

$$n = \beta \, (d^*)^{\delta} \tag{20}$$

where

$$
\begin{aligned}
\beta &= -0.225\, F^{-0.699} \qquad & 0.2 &< F < 0.55 \\
\beta &= -0.342 \qquad & 0.55 &< F < 0.8
\end{aligned}
\tag{21}
$$

and

$$
\begin{aligned}
\delta &= -0.118\, F^{-0.356} \qquad & 0.2 &< F < 0.55 \\
\delta &= -0.146 \qquad & 0.55 &< F < 0.8
\end{aligned}
$$

$$\log \alpha = a + b \log(d^*) + c \log^2(d^*) \tag{22}$$

where

$$
\begin{aligned}
a &= \frac{-0.6}{F} \\
b &= 0.75\, F^{-1.125} \\
c &= 2.653\, F - 1.95
\end{aligned}
\tag{23}
$$

Using Equations 19 through 23, H_m can be determined given the vessel speed, displacement, water depth, and distance from the sailing line. These equations are valid for vessel Froude numbers from 0.2 to 0.8, which are common for most vessel operations.

This model was subsequently improved by modifying the value of H_m^* calculated from Equation 19 (called $H_m^*(19)$) by the following relationship:

$$
H_m^* = A'\, H_m^*(19) - B' \tag{24}
$$

where A' and B' attempt to better include the effects of hull geometry. Table 1 is a tabulation of A' and B' values for vessel types used in the model development, where A' and B' are a function of the block coefficient, dimensionless length, dimensionless beam, and dimensionless draft defined as follows:

$$
\begin{aligned}
&\textit{Block Coefficient} &&= \frac{W}{(\gamma_v LBD)} \\
&\textit{Dimensionless Length} &&= \frac{L_v}{W^{1/3}} \\
&\textit{Dimensionless Beam} &&= \frac{B}{W^{1/3}} \\
&\textit{Dimensionless Draft} &&= \frac{D}{W^{1/3}}
\end{aligned}
$$

where γ is the specific weight of water.

Model 9 (Bhowmik et al.)

Bhowmik et al. (1991) measured the waves generated by 12 different recreational type vessels (246 test runs) ranging in length from 3.7 to 14.3 m and draft from 0.1 to 0.76 m. Vessel speeds ranged from 3.2 to 20.3 m/sec. From a regression analysis of all of the data, they developed the following equation

$$
H_m = 0.537\, V^{-0.346}\, x^{-0.345}\, L_v^{0.56}\, D^{0.355} \tag{25}
$$

Table 1
Coefficients A′ and B′ for Weggel and Sorensen Model

Vessel Type	Investigator	Block Coefficient	Dimensionless Length	Dimensionless Beam	Dimensionless Draft	A′	B′
Prototype (various types)	Sorensen (1967)	Varies	Varies	Varies	Varies	1.00	0.000
Cruiser	Das (1969)	1.177	5.517	0.679	0.226	3.52	0.078
Box models	Sorensen (1966b)	0.897	4.313	0.719	0.359	2.60	0.063
Barge	Hay (1967)	0.861	4.726	0.977	0.251	1.53	0.005
Barge	Bidde (1968)	0.797	4.869	0.977	0.259	2.17	0.030
Moore dry dock tanker	Hay (1967)	0.691	5.834	0.764	0.324	2.55	0.036
Auxilary supply vessel	Hay (1967)	0.629	4.922	1.141	0.283	1.89	0.025
Mariner class cargo ship	Hay (1967)	0.526	6.357	0.831	0.270	0.84	0.007
Mariner class cargo ship	Bidde (1968)	0.526	6.357	0.831	0.270	0.91	0.010
Mariner class cargo ship	Das (1969)	0.526	6.357	0.831	0.270	0.73	0.008
Ferryboat	Kurata & Oda (1984)	0.514	5.343	0.949	0.384	3.19	0.179
Tugboat	Hay (1967)	0.475	4.670	1.050	0.429	1.73	0.015
Tugboat	Kurata & Oda (1984)	0.321	4.801	1.470	0.441	3.30	0.145

where metric units are to be employed in calculations.

The length and draft of the vessel are employed but no account is taken of the various hull forms (V-hull, johnboat, tri-hull, pontoon and cabin cruiser). The water depth is not included in the equation which would be reasonable for operational conditions where F < 0.7 (but for some of the test runs the depth Froude number significantly exceeded 0.7). The exponent of the term for the distance from the sailing line x (-0.345) is close to the theoretical value discussed in Havelock (1908). However, the exponent of the vessel speed term V (-0.346) indicates that the wave height is inversely and weakly proportional to the vessel speed. The logic of this is hard to understand.

Discussion of Predictive Models

The characteristics of a wave for a given water depth are completely defined by the wave height, period, and direction of propagation. For vessel waves, the wave period and direction (also the wave length and celerity) can be calculated from Equations 1, 3 or 4, 5, and 6. The wave period and direction are dependent only on the vessel speed and water depth and can be directly determined analytically. When the Froude number is less than about 0.7, $\theta = 35°16'$ and the following simplified relationships result:

$$C = 0.816\,V \tag{26}$$

$$L = \frac{2\pi\,C^2}{g} \tag{27}$$

$$T = \frac{2\pi C}{g} \tag{28}$$

As discussed above, prediction of the vessel-generated wave height is a much more complex undertaking. It depends on factors other than just the vessel speed and water depth. Thus, prediction of vessel-generated wave heights involves much more uncertainty. The nine wave height models presented above all yield a value for H_m, the maximum wave height in a wave record. Some authors employ the energy density of this peak wave which is simply $\gamma H_m^2/8$.

Any parameter that indicates the average wave height or the energy of the wave record will depend on the length of record being considered. Thus, any such value would be somewhat arbitrary and must be well defined when used. A typical wave record for a single vessel will consist of an initial group of high waves which contain a major portion of the wave energy. This is followed by significantly lower waves which progressively decrease in amplitude as the record extends. According to the linear wave theory, the energy E in a water wave for a unit width along the wave crest and for one wave length is given by

$$E = \frac{\gamma H^2 L}{8} \tag{29}$$

The wave length for a given water depth depends only on the wave period (see Equations 5 and 6 or Equations 27 and 28 combined by eliminating C). Thus, for a typical vessel wave record where the wave period is relatively constant in the initial group of large waves, the energy content in each wave is dependent essentially on the wave height squared. Given this, perhaps the most logical way to derive a quantitative indication of vessel wave energy is to sum the energy in the waves that have a height higher than 10 percent of the maximum height (or 10 percent of the average of the highest two or three waves). This would yield a repetitive approach to evaluating wave records for energy content, and waves having less than 10 percent of the maximum wave height would have less than 1 percent of the energy of the maximum wave. This approach would also be reasonable for a vessel combination such as a multibarge tow which might generate several groups of high waves. The total energy in the group or groups would be the sum of the energies in each wave as indicated by Equation 30. Most commonly, for analysis of a wave record, an individual wave is designated by the portion of the wave record between two successive crossings of the water surface upward through the still water line (known as the zero-upcrossing method).

It is hard to compare the nine wave height prediction models in a directly quantitative way. Qualitatively, some of the models (i.e., 1, 2, and 5) neglect wave height decay with distance from the sailing line, a factor of importance in all cases except for narrow canals. Some of the models (i.e., 1, 2, 3, 5, and 9) do not consider variations in hull geometry in any way and model 6 in only a limited way. Some models (i.e., 3, 5, and 9) have an apparently incorrect relationship between vessel speed and maximum wave height. Only three models (i.e., 4, 7, and 8) pass this qualitative evaluation, and they have limitations for general use.

The Gates and Herbich (1977) model was developed for large seagoing vessels and a Froude number less than around 0.7. It could be improved for general use by the definition of K_w and L_e for additional vessels. The wave height is a function of the vessel speed squared. Perhaps some other power of the velocity head might produce a better empirical fit to experimental data.

A formulation like Equation 16 would be useful if either A'' were provided for more vessel types or sufficient data were available to develop the K value in Equation 17.

The Weggel and Sorensen (1986) model is the most general in including all of the dependent factors. Even though it attempts to include vessel hull form, it does so in a somewhat indirect and limited way. Perhaps the coefficients A' and B' could be better formulated and more directly related to specific bow geometry parameters, given sufficient bow geometry data and related field data on generated wave heights.

Wave Height Model Evaluation

The best way to evaluate these models is to compare them to measured data. The data sets used for this comparison must satisfy three criteria:

a. They must not be data sets that were used to develop the model since all models contain a large element of empirical calibration or involve direct regression fitting of empirical data.

b. There must be sufficient information available, particularly on the vessel hull characteristics, to apply the model. The requirements of each model vary as to what information is required.

c. The experimental data should be for vessels having hull shapes somewhat similar to the recreational vessels that commonly operate on the Upper Mississippi River System.

As discussed above, the three models that are worthy of evaluation are those of Gates and Herbich (1977), PIANC(1987)/Verhey and Bogaerts(1989), and Weggel and Sorensen (1986). This evaluation follows.

Zabawa and Ostrum (1980) collected field data for a 26-foot-long cruiser having a deep V-hull. The vessel sailing lines were located 200 ft, 150 ft, and 100 ft from a wave gauge. The water depths at the three sailing lines were 13 ft, 12 ft, and 10 ft respectively, but the water depth at the gauge was only 2.2 ft. For the range of vessel wave periods (1.4 to 3.3 sec), calculations using linear wave theory indicate that wave shoaling would vary the wave height by about ± 7 percent between the generation point on the sailing line and the wave gauge. This does not include possible effects of wave refraction as the waves propagate over an uneven bottom to the wave gauge. The neighboring bottom hydrography was not given, so possible refraction effects could not be evaluated.

The general shape of the hull and the vessel length were the only information given on the vessel (beam, draft, and displacement were not given). Thus, only the PIANC(1987)/Verhey and Bogaerts(1989) method could be compared with the data. Also, many of the data runs were for vessel speeds that produced depth Froude numbers in excess of unity. Figure 6 shows a plot of the usable experimental data for the travel distances of 100, 150, and 200 ft. The data scatter widely showing a general trend of wave height increase with increasing vessel speed. The decrease in wave height with distance from the sailing line is not well defined. Also shown on Figure 6 are the predicted wave heights for travel distances of 100 and 200 ft using $A'' = 1.00$ (see Equation 16 where d is taken as the water depth at the sailing line).

Considering the scatter of the data, the PIANC(1987)/Verhey and Bogaerts (1989) procedure does reasonably well at matching the data. However, close inspection of Figure 6 suggests that the increase in wave height with increase in vessel speed might be too sharp. For example, Equation 16 has the maximum

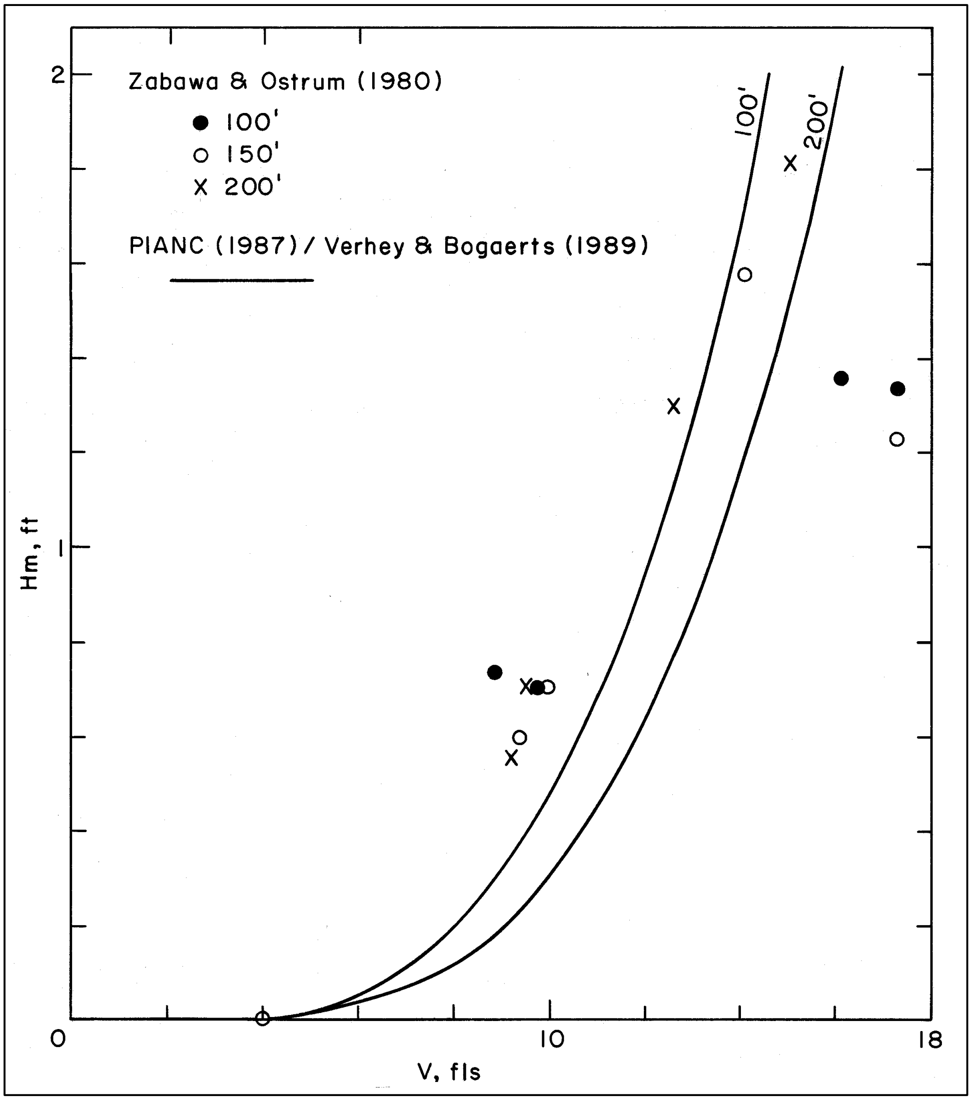

Figure 6. Zabawa and Ostrum (1980) field data compared with predicted results from the PIANC (1987)/Verhey and Bogaerts (1989) model

wave height increase as a function of vessel speed raised to the fourth power, whereas a lower power of vessel speed might be more appropriate.

Ofuya (1970) measured the waves generated by a 25-ft-long cruiser having a beam of 10 ft, a draft of 1.42 ft, and a displacement of 2.5 tons. The wave gauge was in water 25 ft deep, and the vessel sailing lines were 40, 150, 250, and 800 ft from the wave gauge where the water depths were 27, 30, 31, and 33 ft, respectively. For these water depths and typical vessel-generated wave periods, shoaling and refraction effects should not be a problem. The Ofuya (1970) data are plotted in Figure 7. There is the expected trend of increasing wave height with increasing vessel speed as well as a general trend of decreasing wave height with distance from the sailing line, but a fair amount of scatter is also present in the data.

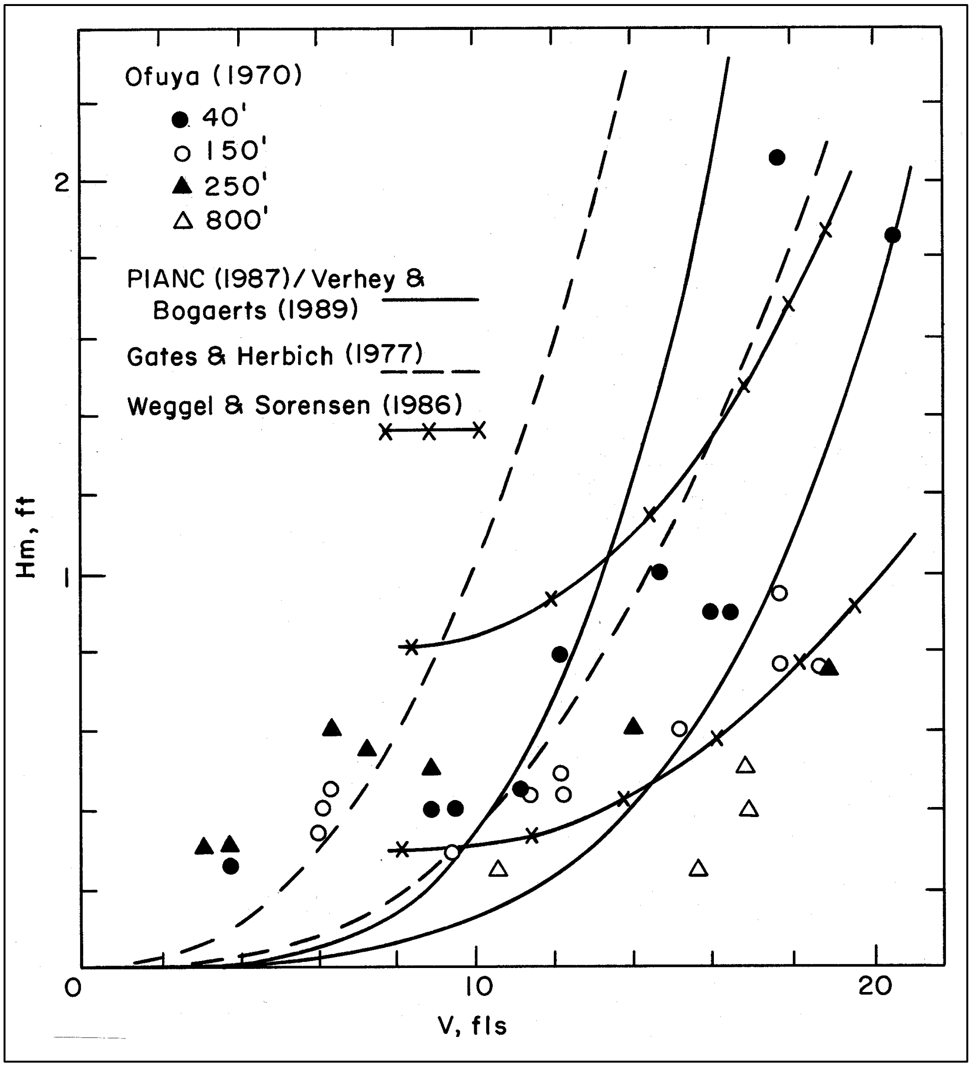

Figure 7. Ofuya (1970) field data compared with predicted results from the PIANC (1987)/Verhey and Bogaerts (1989), Gates and Herbich (1977), and Weggel and Sorensen (1986) models

Sufficient data are given on the vessel hull to apply all three of the models that are being evaluated. The results of these three models are shown in Figure 7 for wave travel distances of 40 and 800 ft which bracket the experimental distances. For the PIANC(1987)/Verhey and Bogaerts(1989) model, the value A'' = 1.0 was again used. For the Gates and Herbich (1977) model and a vessel length of 25 ft, Equation 11 was used to calculate L_e = 8.95 ft which appears to be reasonable. The value of K_w was determined to be 1.13 from Figure 5. The values of H_m were calculated at the cusp points closest to 40 ft and 800 ft, and interpolated values for 40 ft and 800 ft were determined (where cusps might not actually be located). For Weggel and Sorensen (1986), A' = 1.0 and B' = 0 were used. (Values of A' = 3.52 and B' = 0.78, which are based on the Das (1969) laboratory data for a cruiser, were also tried but gave predicted wave heights that were much too high for a given vessel speed.)

Inspection of Figure 7 indicates that none of the models match the experimental data over the full range of vessel speeds. The Gates and Herbich (1977) model underpredicts wave heights at the lower speeds and overpredicts heights at the higher speeds. A similar assessment can be made of the PIANC(1987)/Verhey and Bogaerts (1989) model, which more extremely underpredicts wave heights at low speeds but less extremely overpredicts heights at the higher speeds. The latter model may be the preferred of the two as there is usually more interest in the higher vessel speeds for design conditions. But, again, the fact that the wave height is a function of the vessel speed to the fourth power in this model does not seem to fit very well the trend of the data at the higher speeds. Particularly at the higher speeds, the best fit to the data appears to be the curves generated by the Weggel and Sorensen (1986) model. This model overpredicts wave heights at the very low speeds. (And, it produces the anomolous result of not extrapolating to zero height at zero speed.) Adjustment of the A' and B' values for this model could somewhat improve its fit to the data.